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THE WAVE DISTRIBUTION FUNCTIONS OF PLASMASPHERIC ELF HISS: GEOS 1 OBSERVATION IN THE EQUATORIAL REGION

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Abstract: The wave distribution functions of plasmaspheric ELF hiss have been determined at the equatorial region inside the plasmapause, by applying the maximum entropy method to the data observed by GEOS 1 satellite. Three equatorial events have been analyzed, and it is found that just inside the plasmapuse, the wave normal direction θ of ELF hiss is nearly aligned with the magnetic field, and when the observing position is 0.3–0.5 R_e (R_e: earth's radius) inside from the plasmapause, there are two different groups of wave normal angles; one is a medium wave normal angle ranging from 20° to 60° and the other is a large wave normal in a range from 70° to 80°, slightly smaller than the Gendrin angle.

The present direction finding results of equatorial ELF hiss have been extensively compared with the previous theoretical model to discuss the generation mechanism of plasmaspheric ELF hiss. Then, it is concluded that some of the plasmaspheric hiss emissions are generated by the cyclotron instability with $\theta \cong 0°$, initially proposed by R. M. THORNE *et al.* (J. Geophys. Res., **78**, 1581, 1973), but a considerable number of ELF hiss emissions seem to be generated at large wave normals.

1. Introduction

Broadband and structureless whistler mode noises in the ELF/VLF frequency range are known to be persistent within the plasmasphere (GURNETT and O'BRIEN, 1964; TAYLOR and GURNETT, 1968; RUSSELL *et al.*, 1969; DUNCKEL and HELLIWELL, 1969) and THORNE *et al.* (1973) have referred to them as "plasmaspheric hiss". Since plasmaspheric hiss appears to play an important role in the formation of the electron slot between the inner and outer radiation belts (LYONS *et al.*, 1972; LYONS and THORNE, 1973), studies have been devoted to its generation and propagation mechanism.

THORNE *et al.* (1973) have made detailed analyses of the OGO 5 wave data, together with some direction finding results, which have led them to conclude that plasmaspheric hiss is generated with its wave normal aligned with the magnetic field, just inside the plasmapause by the cyclotron instability due to medium energy (10–100 keV) electrons. The generation mechanism of cyclotron instability such as suggested by KENNEL and PETSCHEK (1966) and ETCHETO *et al.* (1973), requires a continuous source of longitudinal waves at the equator. In other words, the mechanism can be maintained by amplified waves being returned to the growth region after a reflection at the top of the ionosphere (ducted waves) or after a magnetospheric reflection (non-ducted waves). For both processes, too small an amount of wave energy is reinjected to the source region, to maintain the process. Then, THORNE *et al.* (1979) have suggested that waves, which have been amplified, are returned to the growth region on quasi-cyclic orbits as the consequence of an internal reflection at the plasmapause, as a possible maintenance of the hiss, which has led them to call those waves "cyclic waves". Very recent studies by HUANG and GOERTZ (1983) and HUANG *et al.* (1983) have shown, based on the calculations of ray path integrated gains, that the concept of cyclic ray paths does not provide an explanation for the generation of non-ducted hiss and further that there is a major discrepancy in the intensity levels between the theoretical estimates and the observations. All of these studies are based on the original speculation by THORNE *et al.* (1973) that the waves are initially generated with their wave normals parallel to the magnetic field. On the other hand, CHURCH and THORNE (1983) have made theoretical improvements to above works and they have evaluated the net gain accumulated during several passes across the equator as a function of wave normal angle at the observation point by means of backward ray-tracings in model hot electron distributions. Their result has supported the electron cyclotron growth on quasi-cyclic orbits and has shown that the peak wave amplitude occurs for field-aligned waves near the equator. Hence, these theoretical implications should be compared with the corresponding experimental data in order to study the generation and propagation mechanism of ELF hiss.

Information concerning the distribution of wave normals would be a powerful tool for studying the generation of ELF hiss. LEFEUVRE *et al.* (1983) have shown, based on ISEE measurements, that the peak power in the spectrum around the equatorial plane occurs at oblique wave normal angles and never in the field-aligned direction. In the present paper, we present the direction finding results of plasmaspheric ELF hiss at the equatorial region, inside, but close to, the plasmapause, by using the data by GEOS 1 satellite, and this paper will be very complementary to the work by LEFEUVRE *et al.* (1983). In view of the highly incoherent character of plasmaspheric hiss, it cannot be analyzed well by MEANS' (1972) method based on a single plane wave hypothesis, which has been adopted by THORNE *et al.* (1973) for the analyses for those hiss emissions. On the other hand, the wave distribution function (WDF) method (LEFEUVRE *et al.*, 1981, 1982, 1983; HAYAKAWA *et al.*, 1986) and the maximum likelihood (ML) method to find the propagation directions of a few plane waves (BUCHALET and LEFEUVRE, 1981; HAYAKAWA *et al.*, 1984, 1986) would be entirely appropriate to these hiss phenomena.

The plan of the paper is as follows. Section 2 describes the direction finding data on board GEOS 1 satellite and the analysis method of direction finding (the estimation of wave distribution functions). In Section 3, we report the characteristics and wave normals of three equatorial plasmaspheric ELF hiss events observed inside the plasmapause in the vicinity of the equatorial plane. Finally, Section 4 deals with the summary of the obtained direction finding results, which is compared with the theoretical models in order to clarify the generation mechanism of plasmaspheric ELF hiss.

2. The Direction Finding of Plasmaspheric ELF Hiss

The wave normals of plasmaspheric ELF hiss are determined, using the data observed by GEOS 1 satellite. Its apogee and perigee are 38000 and 2050 km, respectively and the period is 12 h. See KNOTT (1978) for more details of the orbit. The wave data used for direction findings are three magnetic and three electric field components. The data are recorded by a swept frequency analyzer (SFA) system and six SFA's operate as heterodyne systems controlled by a single frequency synthesizer. The analyzers select bands of 300 Hz in the frequency range from 150 Hz to 77 kHz in steps of 300 Hz, thus giving a complete coverage. The transposed signals are sampled with a frequency of 1.488 kHz and the high-pass filter of the 300 Hz SFA is positioned at 150 Hz and the low-pass filter at 450 Hz. For a more detailed description of the wave experiments on GEOS, see JONES (1978) and S-300 EXPERIMENTERS (1979).

The emissions such as hiss are known to be highly turbulent, and so hiss cannot be analyzed satisfactorily by the classical method based on a single plane wave assumption (MEANS, 1972; THORNE *et al.*, 1973). Then, the wave distribution function method (LEFEUVRE *et al.*, 1981, 1982, 1983; HAYAKAWA *et al.*, 1986) or the maximum likelihood method for determining the propagation directions of multiple plane waves (BUCHALET and LEFEUVRE, 1981; HAYAKAWA *et al.*, 1984, 1986) would be very suitable to such phenomena. However, we have utilized only the wave distribution function (WDF) method in this paper. As the electric field components measured by small electric antennas are less reliable, we use the data from three magnetic sensors. In the WDF approach, the wave field is considered as the sum of fields due to a continuum of elementary plane waves of different frequencies propagated in different directions. Such a field can only be described statistically and the solution we choose is the one that has the maximum entropy. The solution is subject to the consideration of stability parameter and prediction parameter (LEFEUVRE *et al.*, 1982).

In what follows, we adopt a Cartesian coordinate system O_{xyz} where the z axis is parallel to the Earth's magnetic field $\tilde{B}_0$, the axis O_x is in the magnetic meridian plane and is directed away from the Earth, while O_y completes the orthogonal set and is directed eastward. The wave normal direction ($\tilde{k}$) is characterized by the polar angle θ between $\tilde{k}$ and $\tilde{B}_0$, and by the azimuthal angle ϕ, the origin of which is O_x (LEFEUVRE *et al.*, 1982; HAYAKAWA *et al.*, 1984, 1986).

3. Characteristics and Wave Normals of ELF Emissions in the Equatorial Region

Table 1 lists the equatorial measurements of plasmaspheric ELF hiss on board GEOS 1, and we describe the characteristics of those emission events and their corresponding direction finding results.

(a) 5th August, 1977

The density measurement has shown that the satellite position where the direction finding is made, is situated at the inner edge of the plasmapause as shown in Table 1. In accordance with the study by THORNE *et al.* (1973) that has yielded a good correlation between ELF hiss cutoff and the density of 100 cm^{-3} of the plasmapause, we have, correspondingly, observed plasmaspheric ELF hiss as shown in Fig. 1a, whose frequency extends up to $\gtrsim 1$ kHz. The direction finding is carried out at the time listed in Table

Table 1. List of equatorial observation of plasmaspheric ELF hiss.

	Date	Time (UT)	Observing location L_{obs}	Geomagnetic coordinates	Plasma parameters (f_{pe}, f_H) (in kHz)	LT (h)	Plasmapause location L_{pp}
Equatorial observations	5 Aug. 1977	1001:08	5.47	(1.2°, 97.5°)	(77.0, 5.01)	11.52	Relatively sharp plasmapause, L_{pp} = 5.50–6.20
	4 Sep. 1977	0800:46	5.27	(4.4°, 99.5°)	(63.12, 6.16)	9.94	Very sharp plasmapause, L_{pp} = 5.8
	28 Sep. 1977	0500:46	4.72	(2.2°, 117.8°)	(54.94, 7.55)	8.35	Very gradual gradient, L_{pp} ~ 5.0

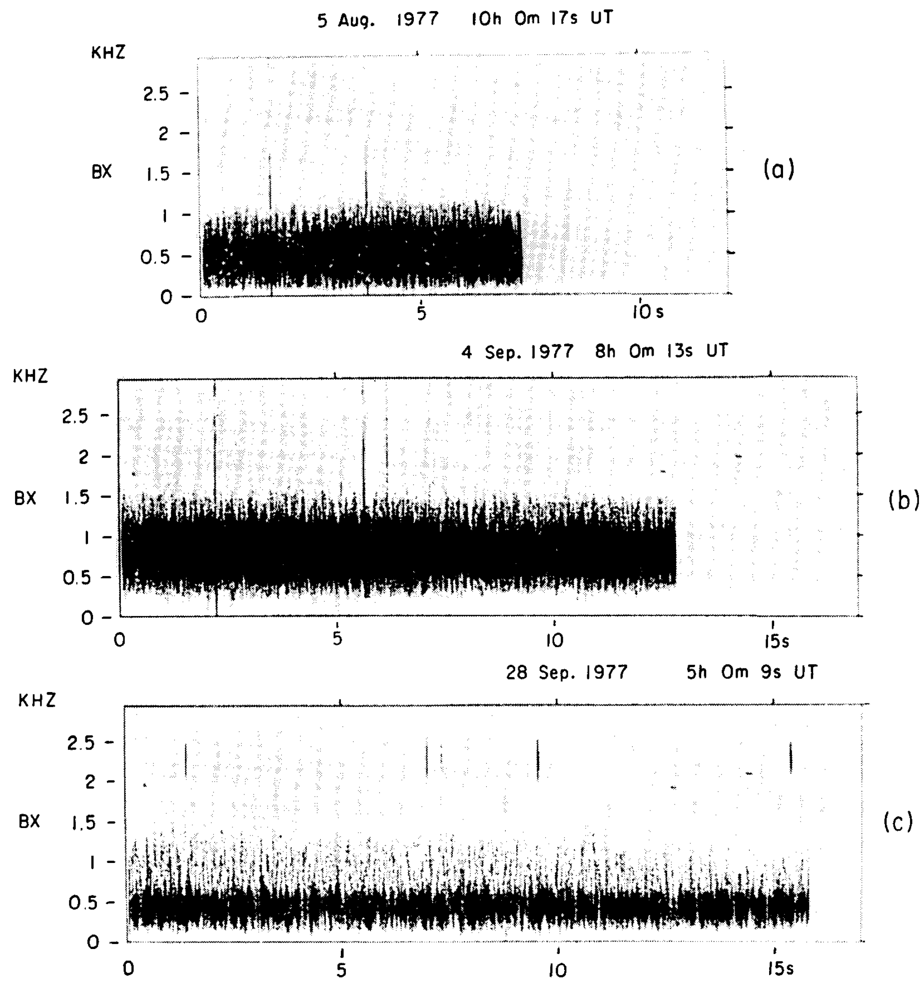

Fig. 1. Spectrograms of plasmaspheric ELF hiss observed at the equatorial region of the plasmasphere. (a) 5th August, 1977, 1000:17 UT. Geomagnetic coordinates = (1.2°, 97.5°), geocentric distance (R/R_e) = 5.47 and L = 5.47. (b) 4th September, 1977, 0800:13 UT. Geomagnetic coordinates = (4.4°, 99.5°), R/R_e = 5.24 and L = 5.27. (c) 28th September, 1977, 0500:09 UT. Geomagnetic coordinates = (2.2°, 117.7°), R/R_e = 4.71 and L = 4.72.

1, about 1 min later than the time of the survey-mode spectrogram in Fig. 1a, and the frequency dependence of the emission intensity at that time is plotted in Fig. 2. The magnetic field intensity of the emission exhibits a rather flat distribution in a range from 300 to 450 Hz, with the peak intensity of $1.2\times10^{-2}\gamma/\sqrt{\mathrm{Hz}}$ at 350 Hz. This value seems to be in good agreement with those reported by previous workers (MUZZIO and ANGERAMI, 1972; THORNE *et al.*, 1973; PARADY *et al.*, 1975).

The direction findings have been made at the two frequencies of 279 and 326 Hz where we expect the enhanced intensity as seen from Fig. 2, and the corresponding contours of the maximum entropy solutions, or the wave distribution functions (WDF), are displayed on polar diagrams in Figs. 3a and 3b, respectively. The scale in the WDF's is linear and runs from 0 to 10. The outermost circle corresponds to $\theta=90°$, while the inner circle (in this case just inside the outer circle) indicates the oblique resonance cone θ_{res} for the whistler mode ($\cos\theta_{res}=f/f_H$). We have presented only the part of the solution with $0<\theta<\pi/2$. As seen from Figs. 3a and 3b, both WDF's are found to exhibit the property of a single peak, although the two figures are very different from each other. The WDF in Fig. 3a is rather elongated in the magnetic meridian plane, but a considerably sharply peaked distribution is found in Fig. 3b. The peaks of both WDF's make very small θ angles with the Earth's magnetic field;

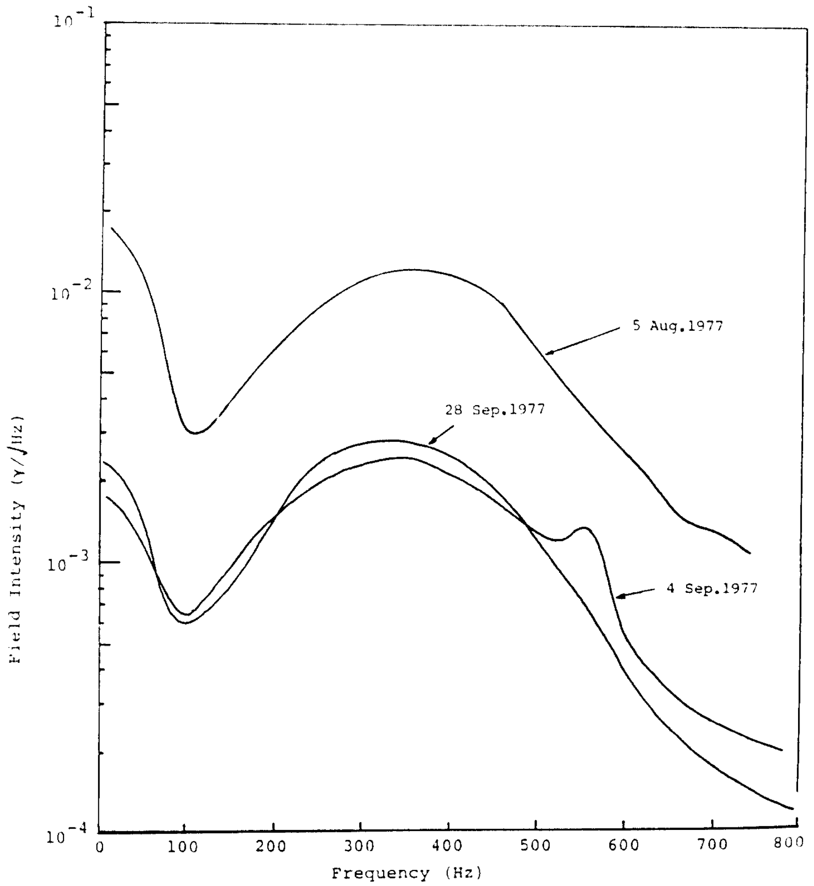

Fig. 2. The frequency dependences of magnetic field intensity of the emissions of three equatorial observations (5th August, 4th and 28th September, 1977).

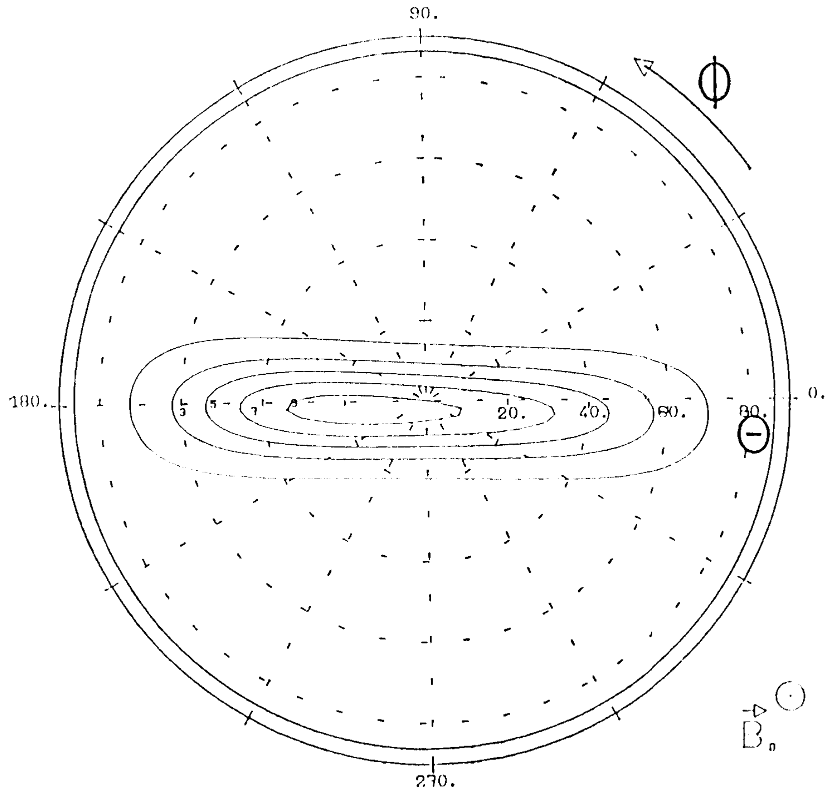

Fig. 3a. f = 279 Hz, the normalized frequency, $\Lambda(=f/f_H)=0.056$, $\theta_{res}=86.8°$, $\theta_g=83.6°$.

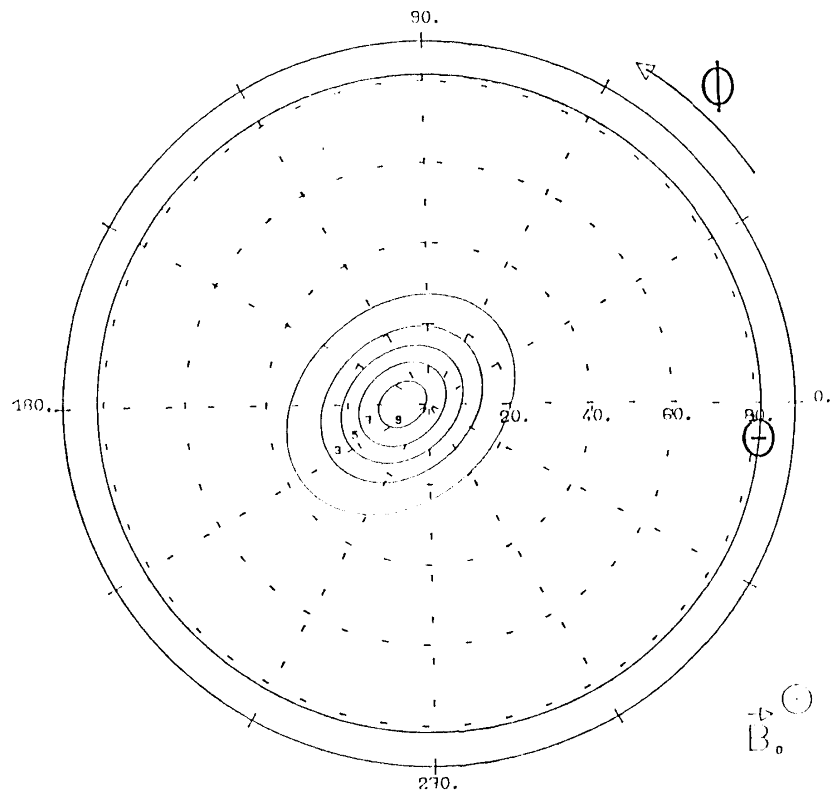

Fig. 3b. f = 326 Hz, $\Lambda=0.065$, $\theta_{res}=86.3°$, $\theta_g=82.5°$.

Fig. 3. Contours of wave distribution functions for the event of 5th August, 1977.

$\theta \sim 15°$ in Fig. 3a and $\theta \sim 5°$ in Fig. 3b. Hence, we can conclude that the ELF hiss emissions for this event observed at the inner edge of the plasmapause, have nearly quasi-longitudinal wave normals.

(b) 4th September, 1977

As is seen from Table 1, the satellite position ($L=5.27$) where the direction finding is made, is obviously inside the plasmasphere by 0.53 R_e from the inner edge of the plasmapause and also is near the equator (geomagnetic latitude, $\lambda_m=4.4°$). Then, we show a spectrogram of the hiss observed at 0800:13 UT in Fig. 1b. The frequency dependence of magnetic field intensity of the emission for which direction findings are made, is given in Fig. 2, which yields that the maximum amplitude takes place nearly at the same fequency as in the previous event, but the peak amplitude is about one fifth that of the previous event.

The WDF's for this event have been presented in Fig. 4 at the following five frequencies; 279 Hz (Fig. 4a), 325 Hz (4b), 418 Hz (4c), 465 Hz (4d) and 575 Hz (4e). The WDF in Fig. 4a is singly peaked, but it has a very broad distribution as compared with the WDF's in Figs. 3a and 3b, such that the energy in Fig. 4a is extended from the peak to both regions close to θ_{res} with ϕ approximately separated by $\sim 180°$. The peak of the WDF takes place at $(\theta, \phi)=(\sim 20°, \sim 285°)$. At the higher frequency of 325 Hz in Fig. 4b, the peak of the energy distribution is positioned nearly at the same place as that in the previous figure, but the distribution becomes less widely distributed. The wave energy close to θ_{res} in the ϕ angle range from $\sim 110°$ to $\sim 150°$ in Fig. 4a becomes very depleted, while the wave energy becomes more enhanced in the ϕ range from $\sim 260°$ to $\sim 320°$. With the increase of frequency to 418 Hz (in Fig. 4c), the energy distribution is highly concentrated to the region in the lower half of the contour map. The distribution seems to be rotated to the larger ϕ region, and the peak of the WDF is located at $(\theta, \phi)=(\sim 30°, \sim 250°)$. When the frequency is increased to 465 Hz (in Fig. 4d), the WDF has changed from the single-peaked to the double-peaked distribution. The main, energetic peak is found to shift to a larger θ value ($(\theta, \phi)=(\sim 70°, \sim 240°)$). A significant secondary peak is found, with energy density of about one half that of the main peak, and the position of the secondary peak is situated at $(\theta, \phi)=(\sim 15°, \sim 80°)$. When the frequency is furthermore increased to 575 Hz as in Fig. 4e, the double-peaked distribution in Fig. 4d has changed back to the single-peaked one. The position of the peak has a large θ angle; $(\theta, \phi)=(\sim 50°, \sim 225°)$, and the wave energy is considerably widely distributed, just as the previous figure.

(c) 28th September, 1977

The plasmapause for this event is not well defined, as compared with the previous two events. The density begins to increase very slowly from $L \sim 6.5$ and attains to $f_{pe}=40$ kHz at $L \sim 5.0$. Hence, the satellite location of $L=4.72$ where the direction finding is made, is presumably inside the plasmasphere, and the observed ELF hiss shown in Fig. 1c exhibits relatively a narrow band. The intensity of the emission event for which we have made the direction findings, is shown as a function of frequency in Fig. 2, which yields nearly the same peak intensity at 350 Hz as in the prevoius two events.

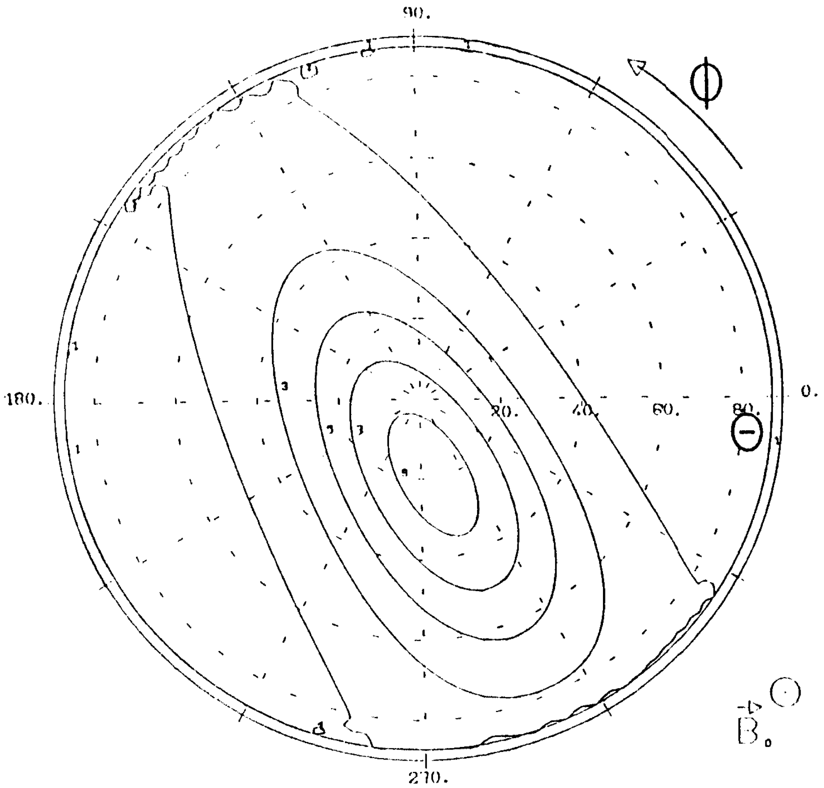

Fig. 4a. $f=279$ Hz, $A=0.045$, $\theta_{res}=87.4°$, $\theta_g=84.8°$.

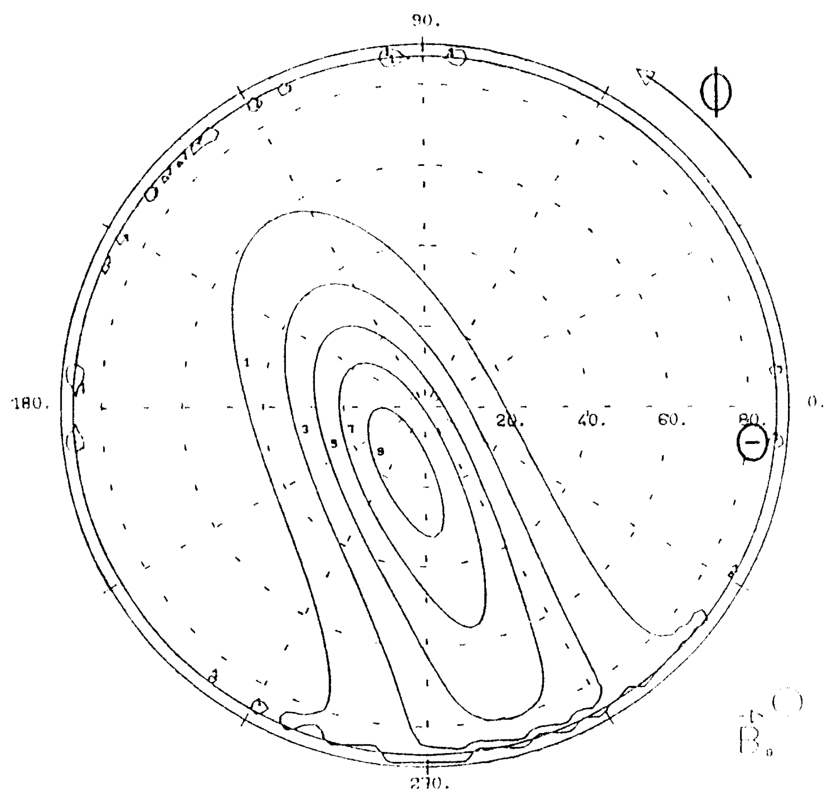

Fig. 4b. $f=325$ Hz, $A=0.053$, $\theta_{res}=87.0°$, $\theta_g=83.9°$.

Fig. 4. Contours of wave distribution functions for the event of 4th September, 1977.

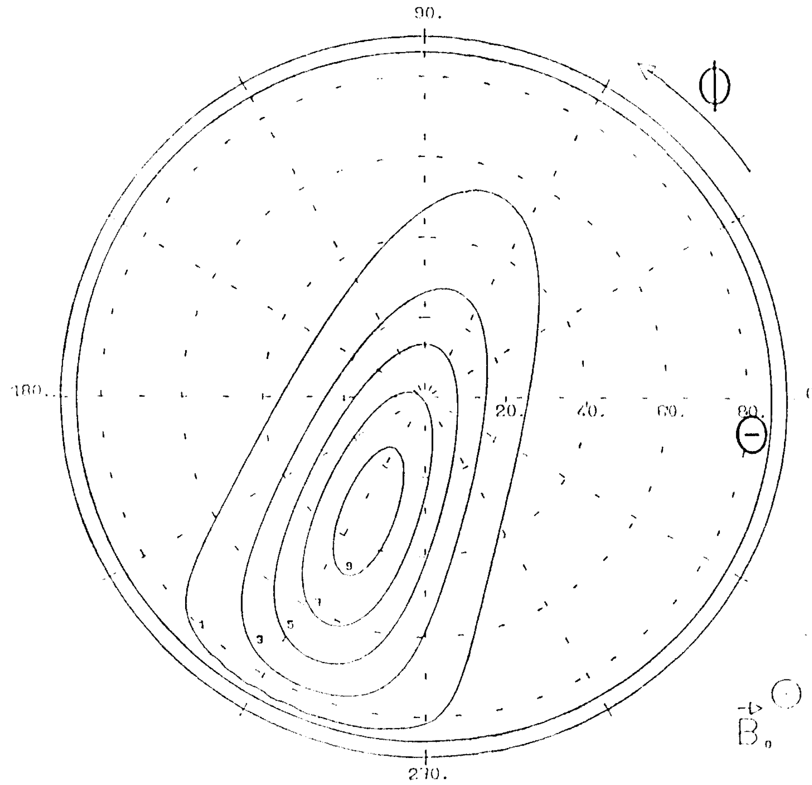

Fig. 4c. $f=418$ Hz, $\Lambda=0.068$, $\theta_{res}=86.1°$, $\theta_g=82.2°$.

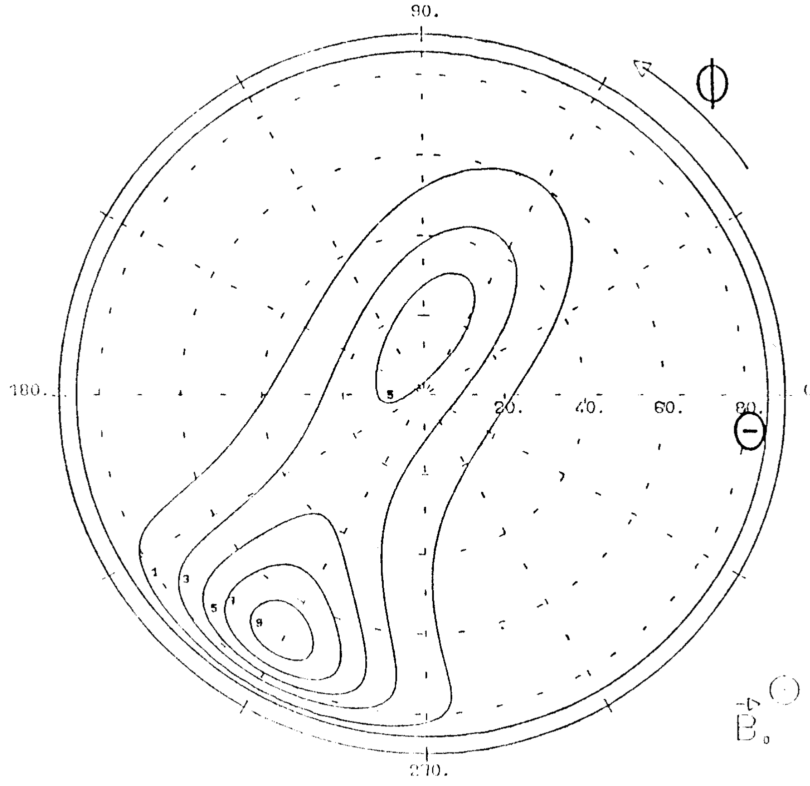

Fig. 4d. $f=465$ Hz, $\Lambda=0.075$, $\theta_{res}=85.7°$, $\theta_g=81.3°$.

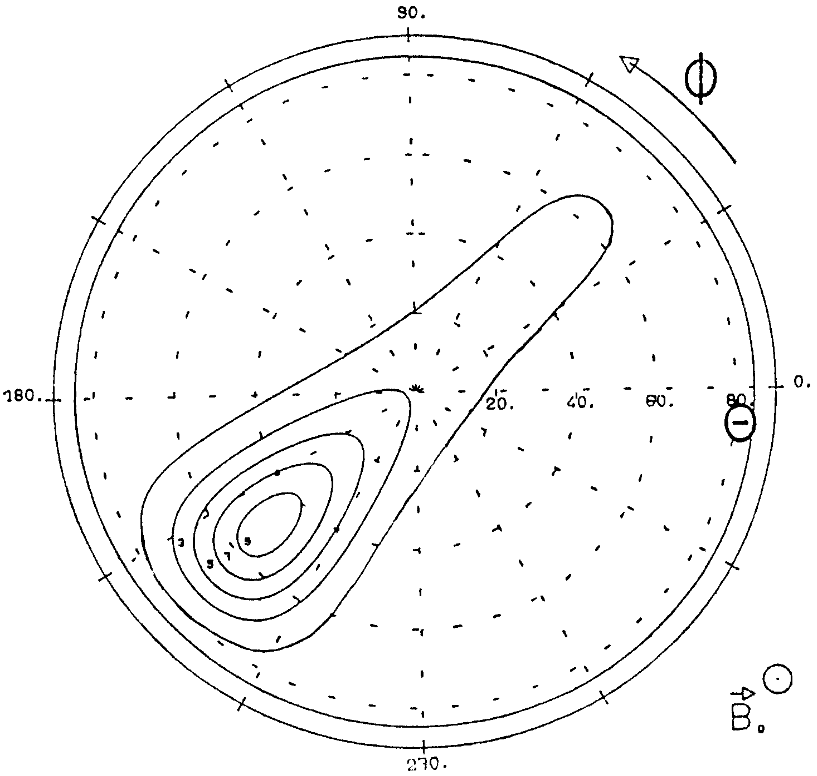

Fig. 4e. $f=575$ Hz, $\Lambda=0.093$, $\theta_{res}=84.6°$, $\theta_g=79.2°$.

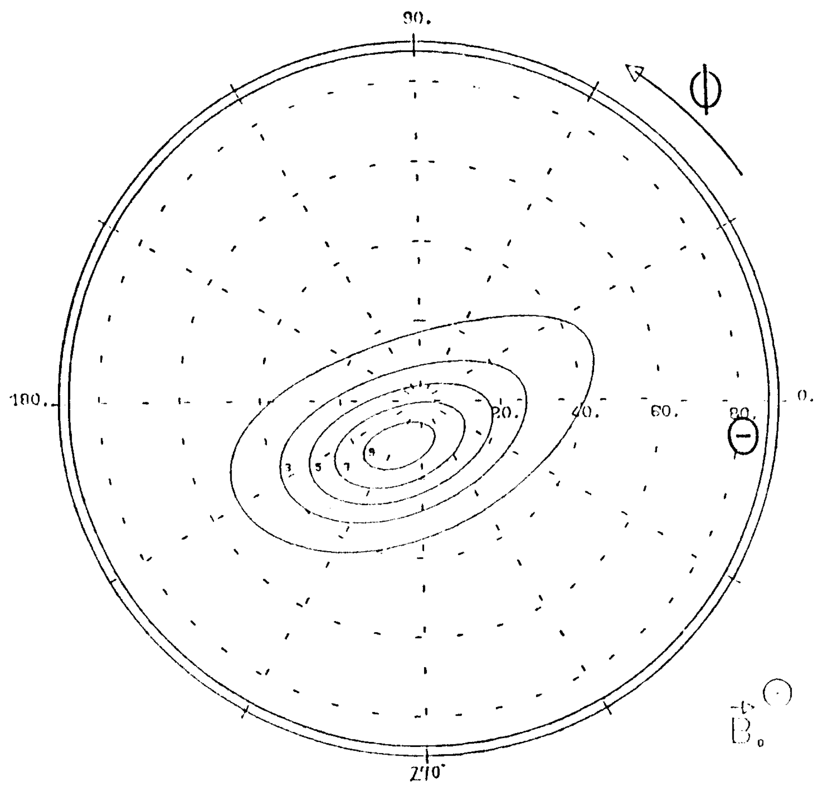

Fig. 5a. $f=325$ Hz, $\Lambda=0.043$, $\theta_{res}=87.5°$, $\theta_g=85.1°$.

Fig. 5. Contours of wave distribution functions for the event of 28th September, 1977.

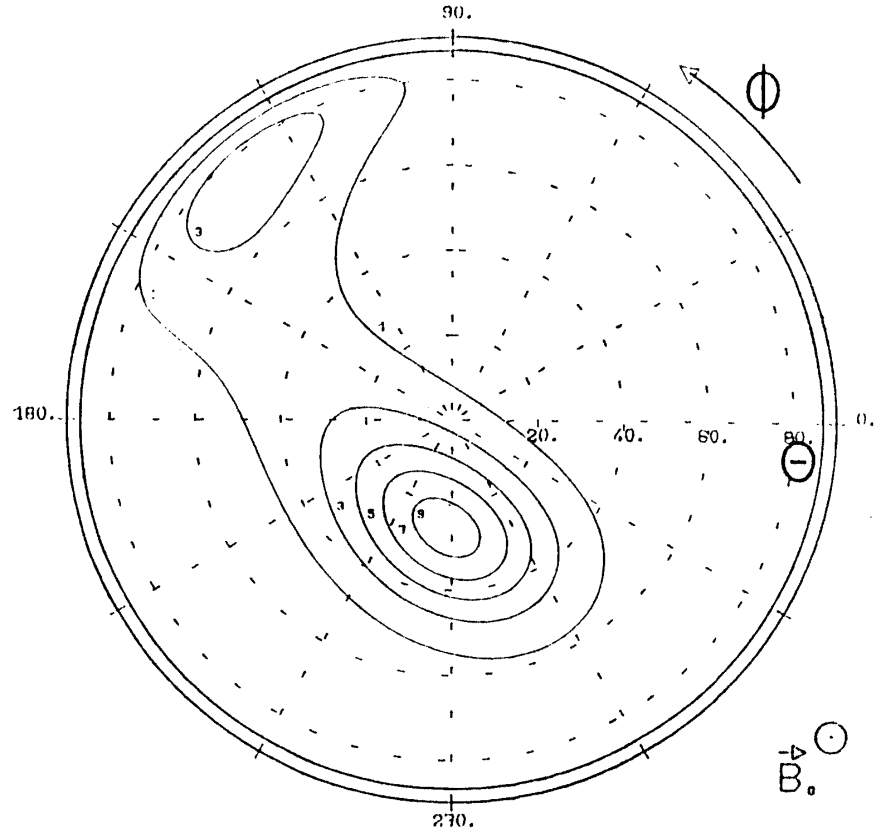

Fig. 5b. $f=418$ Hz, $\Lambda=0.055$, $\theta_{res}=86.8°$, $\theta_g=83.6°$.

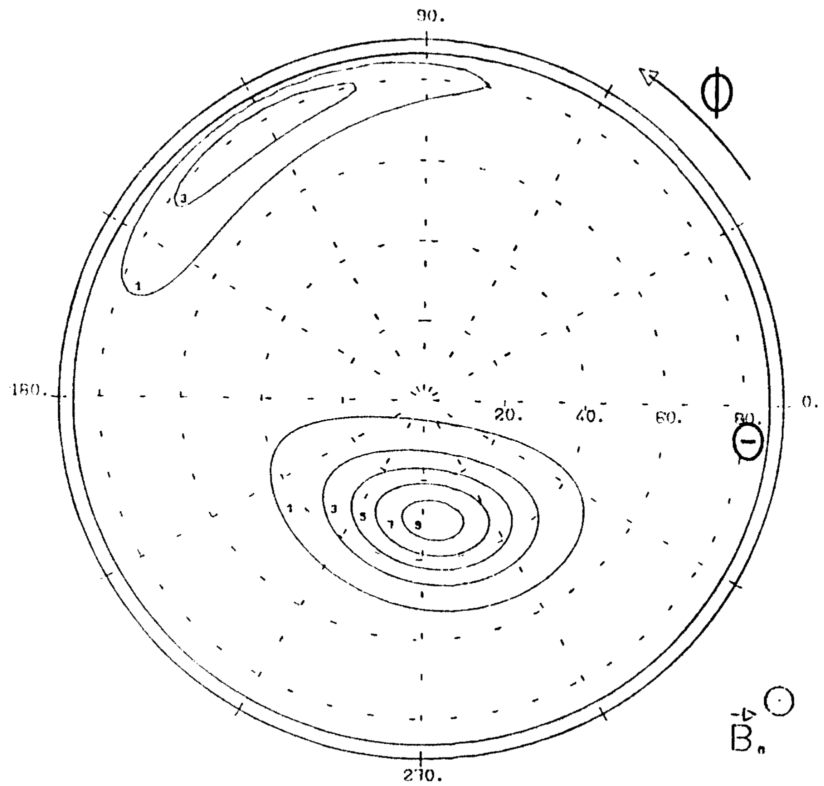

Fig. 5c. $f=465$ Hz, $\Lambda=0.062$, $\theta_{res}=86.5°$, $\theta_g=82.9°$.

The direction findings for this event have been carried out at the three frequencies where the wave energy is maximized, and the contours are presented in Figs. 5a, 5b and 5c. At the lowest frequency of 325 Hz (Fig. 5a), the WDF is relatively sharply peaked, with the energy peak being taking place at $(\theta, \phi)=(\sim 12°, \sim 240°)$. The increase of frequency up to 418 Hz (as in Fig. 5b), has resulted in the appearance of the additional secondary peak, which is not well separated from the main peak. The main peak occurring at $(\theta, \phi)=(\sim 25°, \sim 270°)$ has nearly the same extent as that in Fig. 5a. The secondary peak has the energy ratio of about one third that of the main peak, and appears in the θ region close to the GENDRIN (1961) angle, θ_g (defined as $d(n \cos \theta)/d\theta = 0$, where n is the refractive index). With the increase of frequency to 465 Hz (as in Fig. 5c), the WDF is characterized by being composed of two peaks, whose main and secondary peaks are completely separated from each other, being different from Fig. 5b. The main distribution is well peaked at $(\sim 30°, \sim 275°)$, and the secondary peak has the θ value close to θ_g, but it is considerably spread in the azimuthal driection.

4. Summary of Observed Wave Normal Directions of Plasmaspheric ELF Hiss and Discussion on Its Generation Mechanism

We now summarize the behaviors of wave normal directions of ELF hiss events described in the previous section. For the event of 5th August, 1977, where the satellite is just at the inner edge of the plasmapause, the wave normal of ELF hiss at the two relevant frequencies is nearly aligned with the Earth's magnetic field. For the other two events of 4th and 28th September, 1977 for which the direction finding is made at the equatorial plane, but a little inside from the plasmapause by 0.3–0.5 R_e(R_e: Earth's radius). Two different groups of wave normal directions, the peaks of the WDF's are found; one is a medium wave normal angle ranging from 20° to 50°, and the other is a large wave normal angle, θ=70–80° which is around the GENDRIN angle (θ_g), close to the oblique resonance angle (θ_{res}). We have to add that the normalized frequency, $\Lambda(=f/f_H)$ is less than 0.1 in the present paper.

It is useful to compare our case studies with the recent statistical studies of wave normal directions of ELF hiss observed by the same GEOS 1 satellite by PARROT and LEFEUVRE (1986). However, they have not paid any particular attention to the relative position of the observing point to the plasmapause, though it is a very important factor in the study. According to them, when the observing point is near the equatorial plane such as the geomagnetic latitude $|\lambda_m|$ less than 10°, small wave normal angles ($\theta<30°$) and larger wave normal angles ($40°<\theta<80°$) are simultaneously observed, however, the quasi-longitudinal wave normals are very seldom detected in the high latitudes $|\lambda_m|>10°$. Furthermore, the ϕ distribution of ELF his inside the plasmapause, is shown to be quite uniform over $0°\leq\phi\leq 2\pi$, though we cannot study the behavior of ϕ distribution in the present paper because of the limited data from our case studies. In accordance with their statistical results, smaller θ angles less than 30° are found in the present paper, because it is concerned only with the equatorial observations. Very small θ angles (less than 15°) are found at all frequencies we are interested in, for the event of 5th August, which is believed to be closely associated with the relative position of the observing point with respect to the plasmapause.

While, for other two events, we have found one group with smaller θ angles from $\sim 20°$ to $\sim 50°$ and another group with larger θ angles from 70° to 80°. However, it is not definite from the present paper and the statistical work by PARROT and LEFEUVRE (1986) whether the smaller wave normals are associated with the primary or secondary peak.

Let us compare the present results with the recent similar kind of analyses of ELF hiss on the ISEE satellite by LEFEUVRE *et al.* (1983). Their direction findings are made on four successive orbits in the vicinity of the equatorial plane in a range of L value from 5.0 to ~ 2. We compare our results of equatorial observations with those at their corresponding satellite position ($L \sim 5$). Their finding is that energetic peaks make always very large wave normal angles just around the GENDRIN angle, and the secondary peaks are distributed in a range from $\theta = 40°$ to 60° in the frequency range, $\Lambda = 0.05$ to 0.17. Hence, we find different characteristics of wave normals of ELF hiss on two spacecrafts, ISEE and GEOS 1. However, a common feature from those studies is that the wave normal angles are widely distributed. In our GEOS case, some wave normals are nearly aligned with the magnetic field, but no such waves are found on the ISEE. We cannot know what kind of factors might result in such a discrepancy, but a possible factor might be the relative position of the observing point with respect to the plasmapause.

The direction finding results of our equatorial observations are now used to test the previous theoretical models. THORNE *et al.* (1973) have proposed that plasmaspheric hiss is generated with its wave normal aligned with the magnetic field by the cyclotron instability with medium energy (10–100 keV) electrons diffusing inward from the outer radiation belt. The mechanism can be maintained by amplified waves being returned to the growth region after a reflection at the top of the ionosphere (ducted waves) (KENNEL and PETSCHEK, 1966) or after a magnetospheric reflection (unducted waves). In the former process, too small an amount of wave energy is reinjected and in the latter only oblique waves generally considered as being only weakly amplified, are returned to the equator. Then, more recently, THORNE *et al.* (1979) have shown that the wave propagation including the plasmapause must be carefully considered in the growth rate computations, and they have proposed an importance of "cyclic waves", which have been amplified and followed by returning to the growth region after an internal reflection at the plasmapause. These cyclic waves will have the quasi-longitudinal wave normals at the equator so as to maintain the amplification. Just at the inner edge of the plasmapause (one event in the present paper; 5th August, 1977), the emission seems to be relatively strongly polarized and it may corrrespond to the pulsing hiss as termed by WARD *et al.* (1982). The wave normals of those waves are found to be nearly aligned with the magnetic field, which may provide a support to the existence of plasmapause-guided waves as suggested by the ray-tracing studies by INAN and BELL (1977) and THORNE *et al.* (1979), assuming an initial field-aligned wave normal at the equator just inside the plasmapause. Furthermore, HUANG *et al.* (1983) and CHURCH and THORNE (1983) have demonstrated that ray-path-integrated gains are actually high along the plasmapause because the wave normals of the plasmapause-trapped waves are nearly along the magnetic field to allow further cyclotron amplification. However, on other two events of 4th and 28th September, 1977, many emissions are found to be highly turbulent hiss-type, and to consist sometimes of two plane waves. The larger θ's range from 70° to 80°, slightly smaller than θ_g, while the medium θ values are widely distributed from $\sim 20°$ to $\sim 50°$. It is variable whether the energetic peak is associated with the larger or smaller θ in this study, whereas the work by LEFEUVRE *et al.* (1983) based on the ISEE data has shown that the peak wave energy intensity is always found at oblique was normal angles around θ_g in the equatorial region from $L=5$ to 2. The concept of cyclic ray paths might be reflected in the two wave peaks with smaller wave normals (15°–30°) for the events of 4th and 28th September, 1977, on the basis of the comparison of our observed wave normal behaviors with the result from the three-dimensional ray-path calculations of the integrated gains (due to cyclotron growth and Landau damping) by CHURCH and THORNE (1983) for their model hot electron distributions. They have found that maximum amplification occurs for almost field-aligned waves in the outer plasmasphere and also they have found a general correlation between the zone of wave amplification and the class of waves that internally reflect from the plasmapause, following equatorial transits (cyclic ray paths). For example, the net accumulated gain of the 500 Hz wave observed with $\theta \lesssim 30°$ (which follow a cyclic trajectory) is much higher, by more than 40 dB, than that with $\theta \sim 60°$ (which exhibits no plasmapause encounter and suffers only the magnetospheric reflection) at two selected observation positions of $L=4.5$ and 3.0 in the case when the plasmapause is assumed to be 5.0. However, when we consider that the intensity of very oblique waves such as $\theta=60°$–$80°$ is not so much decreased compared with that of longitudinal waves ($\theta \lesssim 30°$), very oblique waves cannot be explained by the mechanism by CHURCH and THORNE (1983). Then, it is very important to compare the relative location of the observing point with respect to the plasmapause, with the L dependence of the class of ray trajectories, because there is a possible range of launch positions and frequencies for cyclic ray paths for which we can expect higher accumulated net gains for cyclotron instability. The ray-tracing study by THORNE *et al.* (1979) has yielded the range in frequency and in launch position for which we can expect multiple field-aligned equatorial transits, on the assumption of field-aligned initial wave normal at the equator. To be more quantitative based on their results, when the plasmapause is again assumed to be $L=5.0$, the cyclic trajectories at $f=500$ Hz we are concerned with, are expected at the lunch L values from ~ 4.8 to ~ 4.5 (about 0.2–0.5 R_e inside the plasmapause) and also from 4.2 to 3.6. For the two events of 4th and 28th September, 1977, the satellite location is 0.5 and 0.3 R_e, respectively, inside from the observed plasmapause boundary, where cyclic orbits are anticipated to take place. Especially, in the case of 28th September, 1977, the plasmapause position is found to be exactly at $L=5.0$, which was adopted in the theoretical ray-tracing study by THORNE *et al.* (1979). The present study has yielded that oblique waves are, on many occasions, found in the plasmaspheric ELF hiss, giving a further support to the recent finding by LEFEUVRE *et al.* (1983). CHURCH and THORNE's (1983) conclusion based on the cyclotron mechanism that field-aligned waves are most unstable, seems to be in contradiction with the detection of oblique waves in the region where cyclic orbits are expected to occur, which leads us to prefer to adopt the generation of oblique waves. However, ray paths are model dependent, it may be required to carry out the ray-tracings as done by THORNE *et al.* (1979) and CHURCH and

THORNE (1983) for the realistic magnetospheric profile observed simultaneously by the in-situ density measurement at the relevant time, before we come to the conclusion whether the generation of oblique waves is validated or not. Nevertheless, the support to oblique wave generation is given from the recent ground-based measurement at a low $L(L\sim 1.6)$ station (HAYAKAWA *et al.*, 1985).

In concluding the paper, it seems to the authors that some of plasmaspheric ELF hiss emissions are generated by the electron cyclotron mechanism initially proposed by THORNE *et al.* (1973), but a considerable number of them are generated with large wave normal angles. This kind of wave generation with large wave normals for ELF hiss outside the plasmapause, has also suggested by LEFEUVRE and HELLIWELL (1985) who have used the backward ray-tracing to determine the wave normals at the equator considered as the source region, based on the direction finding data obtained in the off-equatorial region. However, it is not certain whether the obtained result for the exohiss can be valid for plasmaspheric ELF hiss. The possible generation mechanism for oblique wave normals might be Cerenkov or Landau instability such as suggested to explain the amplification of magnetospherically reflected whistlers by THORNE (1968), and should be investigated in future.

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